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Citation for published version:

McLeod, DJ, McLure, RJ & Dunlop, JS 2016, 'The $z = 9-10$ galaxy population in the Hubble Frontier Fields and CLASH surveys: the $z = 9$ luminosity function and further evidence for a smooth decline in ultraviolet luminosity density at $z = 8$ ', *Monthly Notices of the Royal Astronomical Society*, vol. 459, no. 4, pp. 3812-3824. <https://doi.org/10.1093/mnras/stw904>

Digital Object Identifier (DOI):

[10.1093/mnras/stw904](https://doi.org/10.1093/mnras/stw904)

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Publisher's PDF, also known as Version of record

Published In:

Monthly Notices of the Royal Astronomical Society

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The $z = 9$ – 10 galaxy population in the Hubble Frontier Fields and CLASH surveys: the $z = 9$ luminosity function and further evidence for a smooth decline in ultraviolet luminosity density at $z \geq 8$

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Accepted 2016 April 14. Received 2016 April 14; in original form 2016 February 18

ABSTRACT

We present the results of a search for $z = 9$ – 10 galaxies within the first eight pointings of the Hubble Frontier Fields (HFF) survey and 20 cluster fields from the Cluster Lensing And Supernova survey with Hubble (CLASH) survey. Combined with our previous analysis of the *Hubble Ultra Deep Field*, we have now completed a search for $z = 9$ – 10 galaxies over $\simeq 130$ arcmin², spread across 29 *Hubble Space Telescope* Wide Field Camera 3/IR pointings. We confine our primary search for high-redshift candidates in this imaging to the uniformly deep, relatively low magnification regions (i.e. $\sigma_{160} > 30$ AB mag for HFF and $\sigma_{160} > 28.8$ AB mag for CLASH in 0.5-arcsec apertures). We unveil a sample of 33 galaxy candidates at $z_{\text{phot}} \geq 8.4$, five of which have primary photometric redshift solutions in the range $9.6 < z_{\text{phot}} < 11.2$. The improved statistics and reduced cosmic variance provided by our new sample allows a more accurate determination of the ultraviolet (UV)-selected galaxy luminosity function (LF) at $z \simeq 9$. Our new results strengthen our previous conclusion that the LF appears to evolve smoothly from $z = 8$ to 9, an evolution which can be equally well modelled by a factor of $\simeq 2$ drop in density, or a dimming of $\simeq 0.5$ mag in M^* . Moreover, we are able to place initial constraints on the $z = 10$ LF, finding that the number density at $M_{1500} \simeq -19.7$ is $\log(\phi) = -4.1^{+0.2}_{-0.3}$, a factor of $\simeq 2$ lower than at $z = 9$. Finally, we use our new results to revisit the issue of the decline in UV luminosity density (ρ_{UV}) at $z \geq 8$. We conclude that the data continue to support a smooth decline in ρ_{UV} over the redshift interval $6 < z < 10$, in agreement with simple models of early galaxy evolution driven by the growth in the underlying dark matter halo mass function.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift.

1 INTRODUCTION

Our understanding of cosmic history within the first billion years after the big bang has improved dramatically in recent times, largely thanks to the near-infrared capabilities of the *Hubble Space Telescope* (HST) as realized through Wide Field Camera 3 (WFC3/IR). It has now become relatively routine to assemble catalogues of galaxies out to $z \simeq 8$, either via colour–colour selection or spectral energy distribution (SED) fitting (e.g. McLure et al. 2010, 2011; Bouwens et al. 2011; review by Dunlop 2013), with the current frontier of observations now at $z \sim 9$ – 10 (e.g. McLure et al. 2013; Oesch et al. 2014; Bouwens et al. 2015b; McLeod et al. 2015).

An important measure of the evolution of the high-redshift galaxy population is the ultraviolet (UV)-selected galaxy luminosity function (LF). To determine the form and evolution of the UV galaxy LF, it is crucial to establish a wide baseline in UV luminosity, and

this can now be achieved by combining the ultra-deep imaging provided by the *Hubble Ultra Deep Field* (HUDF) with the shallower, wider data of the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS) fields, and the still wider, shallower ground-based imaging obtained in the UKIDSS Ultra Deep Survey (UDS) and UltraVista/Cosmological Evolution Survey (COSMOS) fields (Bowler et al. 2012, 2014, 2015; McCracken et al. 2012). Other surveys, such as the pure-parallel HST Brightest of Reionizing Galaxies (BoRG) survey (Trenti et al. 2011) also provide the opportunity to study the bright end of the LF at high redshift via multiple, shallow, pencil-beam pointings. The LF at redshift $z = 6$ – 8 has been the subject of numerous studies in the recent literature, and is now largely well understood at magnitudes fainter than $M_{1500} \simeq -21$ (see McLure et al. 2013; Bowler et al. 2014, 2015; Bouwens et al. 2015a; Finkelstein et al. 2015).

By integrating the luminosity-weighted LF, one arrives at the UV luminosity density (ρ_{UV}), which can then be converted into a star formation rate density (ρ_{SFR} ; see Kennicutt & Evans 2012). As expected, given the agreement in the form of the faint end of the

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LF, the determinations of ρ_{UV} are in general concordance out to $z \sim 8$. Because of observational constraints, the determination of these quantities at even earlier epochs is challenging, and different studies have reached different conclusions.

The first meaningful study of the $z \simeq 9$ galaxy population was undertaken by Ellis et al. (2013) and McLure et al. (2013), based on the small sample of $z \simeq 9$ galaxies uncovered within the HUDF12 data set (which featured the key ultra-deep Y_{105} , J_{125} , J_{140} and H_{160} imaging necessary to identify robust $z \simeq 9$ galaxy candidates; Koekemoer et al. 2013). Based on this sample, Ellis et al. (2013) concluded that the decline in ρ_{UV} beyond $z \simeq 4$ continued relatively smoothly beyond $z \simeq 8$, indicative of a gentle decline of star formation rate density back to earlier epochs, as naturally required to consistently explain cosmic reionization and recent constraints on Thomson scattering optical depth delivered by *Wilkinson Microwave Anisotropy Probe* (WMAP) and *Planck* (e.g. Robertson et al. 2013, 2015). However, in contrast, Oesch et al. (2014) conclude that $z \simeq 8$ marks the onset of a dramatic fall-off in ρ_{UV} , at which the decline of luminosity density switches suddenly from $\rho_{UV} \propto (1+z)^{-3.6}$ to a much more rapid $\rho_{UV} \propto (1+z)^{-10.9}$.

To resolve this disagreement, what is required is more deep near-infrared imaging, including the crucial J_{140} WFC3/IR filter, and ideally involving many different sightlines to minimize the uncertainty introduced by cosmic variance. Such imaging is now being delivered by the Hubble Frontier Fields (HFF) programme, from which the *HST* WFC3/IR imaging has now been released for four clusters and their corresponding parallel fields. The HFF programme has already proven to be instrumental in furthering our knowledge of galaxies in the young Universe, with a number of studies already published on high-redshift galaxy populations (e.g. Zheng et al. 2014; Zitrin et al. 2014; Atek et al. 2015; Ishigaki et al. 2015). One of the primary aims of the HFF survey is to exploit the gravitational lensing provided by the cluster fields to aid the discovery and study of faint galaxies at high redshift. However, as discussed in McLeod et al. (2015) and further below, the parallel pointings also play a significant role in advancing our knowledge of the galaxy UV LF at extreme redshifts.

In McLeod et al. (2015) we analysed the imaging from the first two HFF cluster+parallel pointings to derive improved constraints on the $z \simeq 9$ LF and revisit the issue of the decline in ρ_{UV} at $z \geq 8$. We uncovered 12 galaxies in the redshift range $8.4 < z < 9.5$ from within the area covered by these four WFC3/IR pointings, enabling us to place the best constraints to date on the evolution of the LF from $z \simeq 8$ to $z \simeq 9$. Our main finding was that the decline in ρ_{UV} beyond $z \simeq 8$ was smooth and relatively modest, with ρ_{UV} falling off much less steeply than $\rho_{UV} \simeq (1+z)^{-10.9}$ as claimed by Oesch et al. (2014). Indeed we found that the decline of $\log_{10} \rho_{UV}$ from $z \simeq 6$ to $z \simeq 9$ could be well described by a simple linear function of redshift, extrapolation of which to $z \simeq 10$ agreed with the (albeit highly uncertain) $z \simeq 10$ determination of Oesch et al. (2014).

However, we are still in the regime of small number statistics at $z \simeq 9$ –10, and more data are still required to resolve this important issue. We thus here present a new study of galaxy evolution beyond $z \simeq 8$ which improves on that presented in McLeod et al. (2015) in several respects. First, the available HFF data set has now been doubled by the release of the imaging of the third and fourth cluster and parallel fields (i.e. of MACS 0717 and MACS 1149), and we have now extended our search for $z \simeq 9$ galaxies to include these new WFC3/IR pointings. Secondly, while our most robust results transpire to be driven primarily by the homogeneous survey area provided by the HFF parallel fields, we have also undertaken a thorough analysis of more strongly lensed regions of the imaging,

and in particular have utilized this approach to search for $z \simeq 9$ galaxies in 20 fields from the Cluster Lensing And Supernova survey with Hubble (CLASH) survey. Finally, we have now also searched both the HFF and CLASH data sets for galaxies at $z \simeq 10$.

As important as lensed fields are for searching for the earliest galaxies, especially intrinsically faint objects, extracting robust quantitative information on high-redshift galaxy evolution from gravitationally lensed fields is challenging and often problematic. A number of groups have provided lensing maps for each of the HFF clusters, and similarly Zitrin et al. (2013) have provided two alternative lensing maps for all of the CLASH fields. Unfortunately, the magnifications predicted by the different models are often significantly different, and these discrepancies are often particularly severe in the high magnification regions around the critical lines. This does not just affect the individual candidates in a sample, but also the effective selection volume that one derives for a particular lensed field. Because of these effects, a determination of the LF from a strongly lensed field can be drastically wrong unless the lensing uncertainties can be controlled. Finally, the intracluster light often significantly reduces the effective photometric depth for much of the on-cluster image unless it can be reliably removed.

Because of these issues, in McLeod et al. (2015) we decided to focus our attention on the clean, homogeneously deep regions of the imaging in the Abell 2744 and MACS 0416 fields. While this approach reduced the available search area somewhat, it crucially allowed us to derive well-defined samples from robust cosmological volumes determined from regions of the imaging with negligible or low/well-constrained magnification factors (μ). In the new study presented here, we have retained this deliberately conservative approach to derive our most robust new determination of the $z \simeq 9$ LF, now based on applying this method to all eight available HFF pointings.

However, in an attempt to exploit all the available deep J_{140} imaging, in this study we have supplemented the eight HFF pointings with a search for $z \simeq 9$ –10 galaxies in the CLASH survey (Postman et al. 2012). Although the WFC3/IR imaging of the CLASH clusters is significantly shallower than the HFF imaging, the effective depth of much of the lensed CLASH imaging is comparable to the depth of the unlensed imaging in the HFF parallel fields. Notwithstanding the aforementioned concerns about uncertain lensing magnifications, an attraction of incorporating the CLASH imaging is that it provides a large number of widely separated pointings on the sky, potentially reducing the impact of cosmic variance (see Trenti & Stiavelli 2008).

This paper is structured as follows. In Section 2 we discuss the HFF and CLASH imaging data, and provide a brief description of the selection of our high-redshift galaxy candidates. This includes a discussion of how we have used deconvolved longer wavelength photometry from *Spitzer* Infrared Array Camera (IRAC) imaging to aid in cleaning our sample of potential low-redshift contaminants. In Section 3, we present and discuss our final sample of $z \geq 9$ galaxies and summarize their basic properties. In Section 4 we present our new, updated determination of the $z = 9$ LF from the blank-field method (i.e. constraining galaxy selection to the cleanest, homogeneous regions of the imaging). In Section 5 we extend our analysis to derive the lensed-field LF determination at $z \simeq 9$, and to provide new constraints on the LF at $z \simeq 10$. Finally, in Section 6 we present our new and improved measurement of the early rise of ρ_{UV} , and compare our results to a range of theoretical predictions. Our conclusions are summarized in Section 7.

Throughout the paper we will refer to the following *HST*/Advanced Camera for Surveys (ACS)+WFC3/IR filters:

$F435W$, $F475W$, $F555W$, $F606W$, $F625W$, $F775W$, $F814W$, $F850LP$, $F105W$, $F110W$, $F125W$, $F140W$ and $F160W$ as B_{435} , B_{475} , V_{555} , V_{606} , V_{625} , i_{775} , i_{814} , z_{850} , Y_{105} , J_{110} , J_{125} , J_{140} and H_{160} , respectively. All magnitudes are quoted in the AB system (Oke 1974; Oke & Gunn 1983). For cosmological calculations, we adopt $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 DATA AND CANDIDATE SELECTION

2.1 Observations

2.1.1 Hubble Frontier Fields

In this section we review the optical, near-IR and mid-IR data used in this study. From the HFF survey we utilized the first four clusters and their corresponding parallel fields. For each of these, *HST* imaging was carried out in three ACS wavebands (B_{435} , V_{606} , i_{814}) and four WFC3/IR wavebands (Y_{105} , J_{125} , J_{140} , H_{160}). Global depths for each of the images were calculated from apertures corrected to enclose 85 per cent of the total flux, assuming a point source. In the parallel fields, the median 5σ depths in this format were $B_{435} = 28.8$, $V_{606} = 28.8$, $i_{814} = 28.9$, $Y_{105} = 28.9$, $J_{125} = 28.4$, $J_{140} = 28.3$ and $H_{160} = 28.2$. Note that the MACS 0717 parallel field was typically ~ 0.1 – 0.3 mag shallower than these values due to a higher background level. The HFF cluster fields were also typically shallower than these depths due to source crowding and intracluster light. In the ‘clean’ regions of the cluster imaging the depths are similar to those of the parallel fields.

For the first two cluster/parallel fields, Abell 2744 and MACS 0416, HAWK- K_S data at $2.2 \mu\text{m}$ (PI: Brammer, ESO Programme ID 092.A-0472) were available. For a 1 arcsec diameter aperture, enclosing 75 per cent of total flux, the depth in K_S was typically $\simeq 25.6$ mag. All eight HFF fields had *Spitzer*/IRAC imaging (PI: Soifer)¹ available in channel 1 ($3.6 \mu\text{m}$) and channel 2 ($4.5 \mu\text{m}$). This data typically reaches a depth of $\simeq 24.5$ mag (at 85 per cent of total), although this is specific to the cleaner parallel regions and is subject to the ability to perform effective deconvolution (see Section 2.4).

2.1.2 CLASH

From the CLASH survey we analysed 23 of the 25 available fields, omitting those which did not have any archival IRAC imaging (Abell 1423 and CL J1226) to avoid having any candidates for which there was no available long-wavelength photometry to check for low-redshift contamination. No public K_S -band imaging was available for the CLASH fields. Three of the CLASH fields are also HFF fields, and so our final sample only exploits the superior HFF data for these clusters. The CLASH imaging of these clusters was however still analysed in the same manner, and used in order to check for consistency. Our final analysis of the CLASH candidates is therefore confined to the 20 fields unique to the CLASH survey and with IRAC imaging.

The CLASH imaging used in this study consisted primarily of the optical bands B_{435} , B_{475} , V_{606} , i_{775} , i_{814} , z_{850} and near-infrared wavebands Y_{105} , J_{110} , J_{125} , J_{140} and H_{160} , although some CLASH fields have also been imaged in V_{555} and V_{625} . The median 5σ global depths (at 85 per cent of total assuming a point source) across the CLASH fields were found to be $B_{435} = 26.8$, $B_{475} = 27.1$, $V_{555} =$

27.5 , $V_{606} = 27.4$, $V_{625} = 26.8$, $i_{775} = 26.6$, $i_{814} = 27.1$, $z_{850} = 26.2$, $Y_{105} = 26.8$, $J_{110} = 26.9$, $J_{125} = 26.7$, $J_{140} = 26.7$ and $H_{160} = 26.5$, although in practice there are again significant variations in depth due to varying levels of source crowding and intracluster light. The IRAC imaging² used was in the 3.6 and $4.5 \mu\text{m}$ filters, with a 5σ median depth for both channels of 23.9 mag (at 85 per cent point-source flux). However, the range of 5σ depths varied between 22.5 and 24.2 mag. The CLASH survey also features WFC3/UVIS imaging in the $F225W$, $F275W$, $F336W$ and $F390W$ bands. This data was not included in our SED fitting analysis because the UVIS imaging is significantly shallower than the ACS data. Nevertheless, in compiling the final candidate list, the UVIS imaging was inspected as an extra check against possible contamination by low-redshift interlopers in the sample.

In total, the raw search area provided by the eight HFF pointings, the HUDF and the 20 CLASH pointings totals $\simeq 130 \text{ arcmin}^2$.

2.2 Photometric catalogues

For each of the survey fields, initial photometric catalogues were constructed by running SExtractor 2.8.6 (Bertin & Arnouts 1996) in dual-image mode, using each of the WFC3/IR images longward of the Lyman break at $z \geq 8.5$ as detection images. Additionally, stacks of the relevant near-IR imaging ($J_{125} + J_{140} + H_{160}$, $J_{140} + H_{160}$ & $J_{125} + J_{140}$) were also used as detection images, in order to boost the sensitivity to $z \geq 9$ objects.

Every object detected at $\geq 5\sigma$ in each catalogue was retained, and a master catalogue was produced containing every unique object from all of the detection catalogues. For each object, the highest signal-to-noise ratio detection was propagated to the final catalogue. Given the position of the redshifted Lyman break, it is expected that no candidate would be detected in the optical bands, and so candidates were required to be undetected at the $\leq 2\sigma$ level in every filter shortward of Y_{105} . Various stacks of the optical photometry were also produced in order to further ensure that candidates were robustly undetected shortward of Y_{105} .

The photometry was measured in 0.4 -arcsec diameter apertures in the ACS and Y_{105} filters and in 0.44 , 0.44 , 0.47 and 0.5 arcsec apertures for the J_{110} , J_{125} , J_{140} and H_{160} imaging, respectively. This ensures ≥ 70 per cent of point-source flux is included in the near-IR bands and 80 – 85 per cent of point-source flux in the ACS bands. All fluxes were then corrected to a uniform 85 per cent of total point-source flux for the purposes of SED fitting.

2.3 Local depth analysis

Accurate photometric errors are crucial for obtaining a robust sample of high-redshift galaxies. First, they are used in the optical flux cuts to remove possible low-redshift contaminants, and in the detection band magnitude cut to remove objects that are too faint. Secondly, the SED fitting requires robust photometric errors in order to produce accurate photometric redshifts. Every lensed field in this study is subject to significant variations in the background and depth across the image, which is exacerbated by source crowding and intracluster light. Although less of an issue in the parallel fields, even here there are still slight variations in the depth. Following McLeod et al. (2015), local aperture-to-aperture rms depths were calculated for every object in the photometric catalogues, based on large grids of apertures placed on blank sky regions. Based on the

¹ Program IDs: 90257, 90258, 90259 and 90260.

² Program IDs: 90009, 80168, 40652, 60034, 545 and 50393.

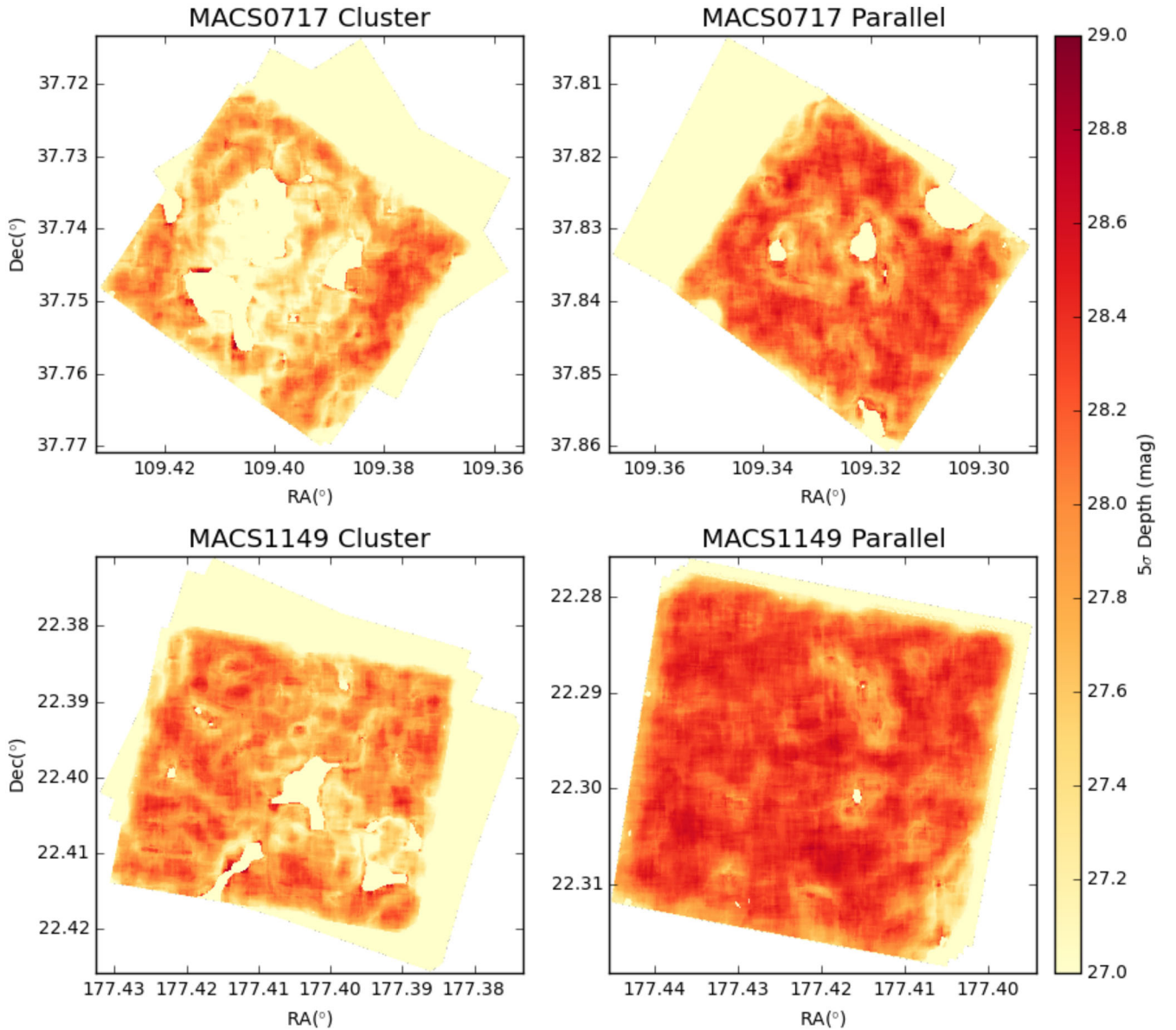


Figure 1. Colour coded H_{160} local depth maps for each of the four new HFF pointings, i.e. the MACS 0717 (top) and MACS 1149 (bottom) cluster fields and their associated parallel fields. Local depths are 5σ measurements for 85 percent of total point-source flux, based on the rms from a grid of 150–200 apertures in the vicinity of each object. For the blank-field methodology used in this study, cuts to the survey area were implemented, culling regions where the 5σ depth was not at least $H_{160} = 28$ mag in this format. For the cluster fields, the effective area is further reduced by the effect of the gravitational lensing of the foreground cluster. Notably, the MACS 0717 cluster field has severe crowding and so is generally shallower than the rest of the cluster fields, providing little extra accessible cosmic volume. The shallower imaging around the edges, due to dithering, was excluded from the search and has been set to a magnitude floor of 27.0 for display purposes. Comparable plots for the first four HFF pointings can be found in McLeod et al. (2015).

rms of the closest 150–200 apertures it was possible to calculate a robust local depth for every object, in every filter. These aperture-to-aperture rms measurements are more accurate in capturing the various systematics than the drizzled rms maps supplied with the data.

By calculating the estimated local depth across the fields, detailed depth maps were produced for each HFF and CLASH field. The depth maps for the new MACS 0717 and MACS 1149 images and their respective parallel fields are shown in Fig. 1, and illustrate the reduced depth in the central regions of the galaxy clusters. It is notable how severe this is for the MACS 0717 cluster field, for which the WFC3/IR imaging is positioned such that the field-of-view is almost completely filled by the cluster. Because of the presence

of a bright star and multiple large bright foreground galaxies, the MACS 0717 parallel image also suffers a significant loss of useful survey area compared to the other HFF parallel images.

2.4 Longer wavelength photometry

In this study we include, where available, Very Large Telescope (VLT) HAWK-I K_S and *Spitzer* IRAC 3.6 and 4.5 μm data. This is primarily to guard against low-redshift interlopers contaminating our $z \geq 9$ galaxy sample. As discussed in McLeod et al. (2015), secondary photometric redshift solutions typically correspond to significantly reddened $z \simeq 2$ galaxies, or galaxies at $z \simeq 6$ with quiescent stellar populations. With the added longer wavelength

photometry, these alternative redshift solutions can usually be robustly excluded or confirmed. Even though the available imaging is significantly shallower than the shorter wavelength *HST* imaging, non-detections can be vital in this process.

Obtaining accurate photometry in the IRAC bands is notoriously difficult given the (relatively) low spatial resolution and the resulting heavy blending of objects in deep imaging. In this study we therefore employed the deconvolution code *TPHOT* (Merlin et al. 2015) in order to extract IRAC and K_s -band photometry. In brief, this code utilizes the positional and surface brightness information of galaxies detected in a high spatial resolution image (HRI) to produce a model of the corresponding low spatial resolution image (LRI). Two-dimensional galaxy templates are extracted from the HRI and convolved with a transfer kernel to match the resolution of the LRI. These low-resolution templates are then used to produce a best-fitting model of the LRI image, in which the flux of each template is fit simultaneously. In this study we used the $J_{125}+J_{140}+H_{160}$ stack as the HRI prior image because it provides the highest signal-to-noise ratio templates for $z \simeq 9$ objects. Full details of the *TPHOT* algorithm can be found in Merlin et al. (2015).

2.5 Photometric redshifts

Once the catalogue was culled of potential low-redshift objects with $\geq 2\sigma$ optical detections, a photometric redshift analysis was performed. For this the SED template fitting code *LEPHARE*³ (Arnouts & Ilbert 2011) was used. The SED template library was based on the models of Bruzual & Charlot 2003 (BC03), utilizing intergalactic medium (IGM) absorption according to the prescription by Madau (1995) and a Calzetti et al. (2000) dust extinction law (allowing reddening to range up to $A_V = 6$). This conservative set of parameters allows highly reddened low-redshift solutions to be considered in addition to any potential high-redshift solution (Dunlop, Cirasuolo & McLure 2007).

Photometric redshift determinations were performed with and without the K_s and IRAC photometry. Objects that had a high redshift ($z \geq 8.4$) primary solution in both runs were retained. Such objects were then visually inspected in all images to check that they were real, and that they were not marginally detected in any optical image or optical image stack. Although the primary photometric redshift solutions are largely driven by the Lyman break, the longer wavelength imaging provides improved discrimination between the primary redshift solution and competing low-redshift solutions.

3 HIGH-REDSHIFT GALAXY CANDIDATES

In this section we list all of the robust $z > 8.4$ galaxy candidates that were found in our search of the CLASH and HFF data sets. The basic measured and derived properties of the galaxies in the final sample are provided in Tables 1 and 2. First we discuss the HFF candidates, including those from the two new data releases. We then discuss the candidates found in the 20 CLASH fields analysed in this study. For a more detailed comparison with previous searches in the first two HFF data sets, the reader is referred to McLeod et al. (2015). Postage stamps of one of the candidates can be seen in Fig. 2, with its corresponding SED in Fig. 3.

3.1 HFF: Abell 2744 and MACS 0416.1–2403 cluster and parallel fields

In McLeod et al. (2015) we found 12 galaxies in the redshift range $8.4 \leq z_{\text{phot}} < 9.5$ in the cluster and parallel fields of Abell 2744 and MACS 0416, a number of which have also been found by other studies (e.g. Zheng et al. 2014; Zitrin et al. 2014; Coe, Bradley & Zitrin 2015; Ishigaki et al. 2015). However, the IRAC photometry was not included in the SED fitting performed in McLeod et al. (2015). A re-analysis of these fields using both K_s and IRAC data recovers all of these galaxies in the redshift range of interest. Notably, one extra candidate is included from the MACS 0416 parallel field. HFF2P-9-5 was found in the McLeod et al. (2015) study, but was deemed too insecure to be included in the final sample. However, thanks to the inclusion of the longer wavelength IRAC photometry, this candidate now has a secure primary redshift solution of $z_{\text{phot}} = 9.1^{+0.7}_{-0.5}$.

3.2 HFF: MACS J0717.5+3745 cluster and parallel fields

The imaging of the MACS J0717.5+3745 field constituted the third data release from the HFF programme. A study of the cluster field by Kawamata et al. (2016) produced no $z \sim 9$ galaxy candidates. Most recently, a study of the cluster and parallel field by Laporte et al. (2016) also revealed no $z \sim 9$ candidates. Our new, independent, analysis also reveals no credible $z \geq 9$ galaxy candidates in either the cluster or the parallel field. As noted previously, the effective area of the MACS 0717 cluster field is much lower than that of the other HFF fields, due to severe source crowding which reduces the depth over much of the image.

3.3 HFF: MACS J1149+2223 cluster and parallel fields

The MACS J1149+2223 cluster field was previously studied as part of the CLASH programme and yielded one robust $z \simeq 9$ galaxy candidate, which was identified in the analysis of both Zheng et al. (2012) and Bouwens et al. (2014). In their more recent analysis of the much deeper HFF imaging of the MACS 1149 cluster field, Kawamata et al. (2016) identified four $z \simeq 9$ candidates, one of which was the original object identified from the CLASH data set.

Our analysis of the MACS 1149 cluster field has identified two $z \simeq 9$ galaxy candidates. The first (HFF4C-9-1, $z_{\text{phot}} = 9.3$) is the original CLASH candidate and the second (HFF4C-9-2, $z_{\text{phot}} = 8.7$) is a candidate which also identified by Kawamata et al. (2016). Consequently, there are two $z \simeq 9$ candidates identified by Kawamata et al. (2016) in the MACS 1149 cluster field which do not feature in our final sample. The first of these (HFF4C-Y2 in Kawamata et al.) is included in our original catalogues, but is located in a region of the HFF imaging which is too shallow to be included in our blank-field search area. Our primary photometric redshift solution for this object is $z_{\text{phot}} = 1.1^{+7.2}_{-0.2}$. However, the very flat χ^2 - z distribution means that we cannot rule out the possibility that this object is at high redshift. We cannot rule-out the possibility that the second object (HFF4C-YJ4) is at high redshift either. This object does not feature in our final high signal-to-noise ratio catalogues, simply because it lies close to the cluster core in a region of shallow depth and large (but uncertain) magnification.

Our analysis of the HFF imaging of the MACS 1149 parallel field identifies two new candidates; HFF4P-9-1 at $z_{\text{phot}} = 9.0$ and HFF4P-10-1 at $z_{\text{phot}} = 9.5$. To date, there are no other analyses of the HFF imaging of the MACS 1149 parallel field in the literature.

³ www.cfht.hawaii.edu/arnouts/LEPHARE/lephare.html

Table 1. The final $z \geq 8.4$ galaxy sample in the HFF. Column (1) lists the candidate names, while columns (2) and (3) list their coordinates. Column (4) gives the best-fitting photometric redshift with corresponding uncertainty. Column (5) gives the total observed H_{160} magnitude, measured using a 0.85-arcsec diameter circular aperture, plus a point-source correction for flux outside the aperture. Column (6) gives the median source magnification for the galaxies in the cluster fields – these are estimated given the CATS, Zitrin LTM and Zitrin NFW magnification models for the first two cluster fields. As the latter is unavailable for MACS 0717 and MACS 1149, only the CATS and LTM models were used. The errors are the upper and lower extremes between these values. Columns (7) and (8) give the total apparent magnitude in H_{160} and the total absolute magnitude at 1500 Å, both after demagnification. Column (9) makes reference to other studies which have independently discovered our candidates: 1 – Zheng et al. (2012); 2 – Zitrin et al. (2014); 3 – Bouwens et al. (2014); 4 – Zheng et al. (2014); 5 – Coe et al. (2015); 6 – Ishigaki et al. (2015); 7 – McLeod et al. (2015); 8 – Kawamata et al. (2016).

Candidate ID (1)	RA (J2000) (2)	Dec. (J2000) (3)	z_{phot} (4)	H_{160} (5)	μ (6)	De-mag H_{160} (7)	M_{1500} (8)	References (9)
HFF1C-9-1	00:14:24.93	−30:22:56.15	$8.4^{+0.3}_{-0.2}$	$26.75^{+0.08}_{-0.08}$	$1.5^{+0.6}_{-0.1}$	$27.2^{+0.1}_{-0.1}$	−19.9	4, 5, 6, 7
HFF1C-10-1	00:14:22.80	−30:24:02.71	$9.5^{+0.9}_{-0.0}$	$27.00^{+0.24}_{-0.19}$	$13.2^{+1.8}_{-1.2}$	$29.8^{+0.2}_{-0.2}$	−17.6	2, 4
HFF1P-9-1	00:13:57.33	−30:23:46.27	$8.8^{+0.7}_{-0.2}$	$27.91^{+0.04}_{-0.15}$	–	$27.9^{+0.2}_{-0.2}$	−19.5	6, 7
HFF1P-9-2	00:13:53.64	−30:23:02.48	$9.3^{+0.5}_{-0.6}$	$28.04^{+0.24}_{-0.20}$	–	$28.0^{+0.2}_{-0.2}$	−19.3	6, 7
HFF2C-9-1	04:16:09.40	−24:05:35.46	$8.6^{+0.1}_{-0.1}$	$26.01^{+0.05}_{-0.05}$	$1.7^{+0.1}_{-0.3}$	$26.6^{+0.1}_{-0.1}$	−20.6	7
HFF2C-9-2	04:16:11.52	−24:04:54.00	$8.5^{+0.1}_{-0.2}$	$26.55^{+0.04}_{-0.04}$	$1.7^{+0.2}_{-0.1}$	$27.1^{+0.1}_{-0.1}$	−20.2	5, 7
HFF2C-9-3	04:16:10.35	−24:03:28.49	$8.7^{+1.1}_{-0.5}$	$27.82^{+0.17}_{-0.15}$	$3.3^{+0.1}_{-0.3}$	$29.1^{+0.2}_{-0.2}$	−18.1	7
HFF2C-9-4	04:16:09.02	−24:05:17.18	$8.5^{+0.1}_{-0.5}$	$27.92^{+0.27}_{-0.21}$	$1.9^{+0.5}_{-0.3}$	$28.6^{+0.3}_{-0.2}$	−18.7	7
HFF2C-9-5	04:16:11.09	−24:05:28.82	$8.6^{+0.9}_{-0.6}$	$28.03^{+0.28}_{-0.23}$	$1.4^{+0.2}_{-0.1}$	$28.4^{+0.3}_{-0.2}$	−18.9	7
HFF2P-9-1	04:16:35.97	−24:06:48.08	$8.7^{+0.7}_{-0.3}$	$27.69^{+0.11}_{-0.10}$	–	$27.7^{+0.1}_{-0.1}$	−19.6	5, 7
HFF2P-9-2	04:16:31.72	−24:06:46.77	$9.3^{+0.3}_{-0.6}$	$28.37^{+0.20}_{-0.17}$	–	$28.4^{+0.2}_{-0.2}$	−19.1	7
HFF2P-9-3	04:16:36.43	−24:06:30.44	$8.9^{+0.5}_{-0.3}$	$28.11^{+0.17}_{-0.15}$	–	$28.1^{+0.2}_{-0.2}$	−19.3	5, 7
HFF2P-9-4	04:16:30.43	−24:06:01.13	$8.4^{+0.3}_{-0.4}$	$28.08^{+0.14}_{-0.12}$	–	$28.1^{+0.1}_{-0.1}$	−19.1	5, 7
HFF2P-9-5	04:16:36.40	−24:06:29.63	$9.1^{+0.7}_{-0.5}$	$28.32^{+0.21}_{-0.18}$	–	$28.3^{+0.2}_{-0.2}$	−19.0	
HFF4C-9-1	11:49:33.59	+22:24:45.76	$9.3^{+0.3}_{-0.4}$	$25.58^{+0.02}_{-0.02}$	$8.7^{+0.1}_{-0.1}$	$27.9^{+0.1}_{-0.1}$	−19.4	1, 3, 8
HFF4C-9-2	11:49:33.73	+22:24:48.30	$8.7^{+1.2}_{-0.4}$	$27.98^{+0.29}_{-0.23}$	$9.2^{+1.4}_{-1.4}$	$30.4^{+0.3}_{-0.2}$	−16.9	8
HFF4P-9-1	11:49:37.33	+22:17:35.35	$9.0^{+0.9}_{-0.5}$	$28.32^{+0.35}_{-0.27}$	–	$28.3^{+0.4}_{-0.3}$	−19.0	
HFF4P-10-1	11:49:39.95	+22:17:36.74	$9.5^{+0.2}_{-0.6}$	$27.49^{+0.15}_{-0.13}$	–	$27.5^{+0.2}_{-0.1}$	−19.9	

Table 2. The final $z \geq 8.4$ galaxy sample in the 20 CLASH fields. Column (1) lists the candidate names, while columns (2) and (3) list their coordinates. Column (4) gives the best-fitting photometric redshift along with the corresponding uncertainty. Column (5) gives the total observed H_{160} magnitude, measured using a 0.85-arcsec diameter circular aperture, plus a point-source correction for flux outside the aperture. Columns (6) and (7) give the source magnification for the candidates – these are estimated from the Zitrin LTM Gauss and Zitrin NFW magnification models. Column (8) gives the absolute magnitude at 1500 Å before demagnification. These can be demagnified with μ to find the intrinsic M_{1500} , which was used in the LF calculations. Column (9) makes reference to other studies which have independently discovered our candidates: 1 – Coe et al. (2013); 2 – Bouwens et al. (2014).

Candidate ID (1)	RA (J2000) (2)	Dec. (J2000) (3)	z_{phot} (4)	H_{160} (5)	$\mu_{\text{lrm-gauss}}$ (6)	μ_{nfw} (7)	Magnified M_{1500} (8)	References (9)
A383-9-1	02:48:03.25	−03:32:45.60	$9.0^{+0.5}_{-0.3}$	$27.55^{+0.71}_{-0.43}$	1.4	1.4	−19.8	
A209-9-1	01:31:54.30	−13:36:57.11	$8.4^{+1.0}_{-0.6}$	$26.17^{+0.29}_{-0.23}$	2.5	4.8	−21.1	
A611-10-1	08:01:01.08	+36:03:03.67	$9.9^{+0.4}_{-0.5}$	$27.12^{+0.40}_{-0.29}$	3.0	1.5	−20.3	
M0429-10-1	04:29:37.79	−02:54:02.26	$9.6^{+0.6}_{-0.9}$	$27.33^{+0.47}_{-0.33}$	3.1	1.7	−20.1	
M0647-11-1 ^a	06:47:55.73	+70:14:35.76	$11.2^{+0.3}_{-0.5}$	$25.46^{+0.11}_{-0.10}$	5.6	5.6	−22.2	1
M0647-10-1 ^a	06:47:55.46	+70:15:38.08	$10.3^{+0.5}_{-0.3}$	$26.66^{+0.17}_{-0.15}$	3.2	1.9	−20.9	1
M0647-9-1	06:47:47.76	+70:15:41.98	$8.8^{+0.7}_{-0.8}$	$27.43^{+0.42}_{-0.30}$	3.1	2.1	−19.9	
M1115-10-1	11:15:54.49	+01:29:47.92	$9.6^{+0.3}_{-0.4}$	$26.22^{+0.13}_{-0.12}$	5.7	3.1	−21.2	2
M1115-9-1	11:15:54.85	+01:29:27.58	$9.1^{+0.5}_{-0.4}$	$26.79^{+0.27}_{-0.22}$	5.6	2.7	−20.5	
M1311-9-1	13:10:59.95	−03:10:36.34	$8.9^{+0.7}_{-0.7}$	$27.50^{+0.60}_{-0.38}$	6.1	2.9	−19.8	
M1423-9-1	14:23:49.08	+24:05:13.68	$8.7^{+0.3}_{-0.7}$	$27.09^{+0.40}_{-0.29}$	17.9	20.7	−20.2	
M1423-9-2	14:23:45.89	+24:04:09.54	$8.5^{+0.4}_{-0.5}$	$26.99^{+0.35}_{-0.27}$	9.7	5.5	−20.2	
M1720-9-1	17:20:12.74	+35:36:17.25	$9.2^{+0.4}_{-0.7}$	$26.73^{+0.24}_{-0.20}$	2.9	1.3	−20.6	2
M1931-9-1	19:31:48.83	−26:33:29.33	$8.7^{+0.6}_{-0.8}$	$27.26^{+0.47}_{-0.33}$	2.6	3.5	−20.0	
RX J2129-9-1	21:29:39.91	+00:05:58.79	$8.8^{+0.6}_{-0.5}$	$26.35^{+0.16}_{-0.14}$	2.1	1.4	−20.9	

Note. ^aThese candidates are probably the same triply imaged object, as discussed in Coe et al. (2013).

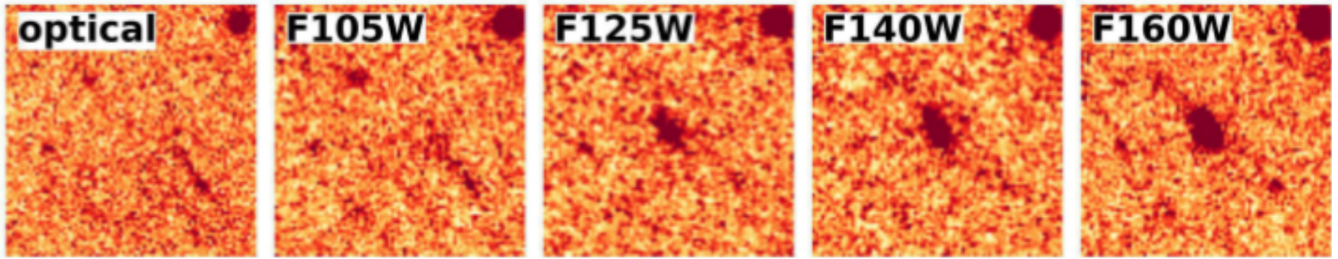


Figure 2. *HST* imaging postage stamps (5×5 arcsec², orientation north = up and east = left) for HFF4C-9-1, a $z_{\text{phot}} = 9.3$ candidate from the MACS 1149 cluster field. Left to right: optical stack, Y_{105} , J_{125} , J_{140} and H_{160} images. Both the stacked optical and Y_{105} images are completely blank, with the object securely detected in all three longer wavelength images. This constrains the break in the spectrum to be at $\lambda \simeq 1.25 \mu\text{m}$ (see Fig. 3). The colour grey-scale is set to the median background flux $\pm 2\sigma$, once any flux from neighbouring objects has been excluded using the segmentation map.

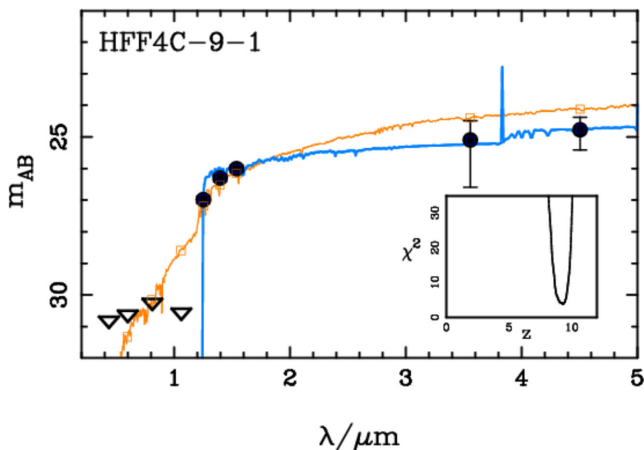


Figure 3. The results of our SED fitting for HFF4C-9-1. The candidate photometry is shown in black, with non-detections plotted at 1σ upper limits. The best-fitting SED model with $z_{\text{phot}} = 9.3$ is shown in blue and the best alternative solution with $z_{\text{phot}} = 2.2$ is shown in orange. The distribution of χ^2 versus redshift is shown in the inset panel. For this candidate the high-redshift solution is strongly preferred, with the alternative solutions shown in the figure separated by $\Delta\chi^2 = 41$. The small squares show the synthetic photometry produced by the two alternative SED models.

3.4 The CLASH survey

In their study of the CLASH data set, Bouwens et al. (2014) found a single $z \simeq 9$ –10 candidate in each of MACS 1115 and MACS 1720 clusters. Our new analysis of the CLASH data set has produced a final sample of 15 galaxy candidates in the redshift range $8.4 < z_{\text{phot}} < 11.2$, including the two candidates previously identified by Bouwens et al. (2014).

Of the 13 candidates in our final sample which were not identified by Bouwens et al. (2014), four have been selected from CLASH clusters which were not analysed by Bouwens et al. (2014). The remaining nine objects either have colours which just fail to satisfy the Bouwens et al. selection criteria, or have photometric redshifts outside the $z \simeq 9.2 \pm 0.5$ range where the Bouwens et al. colour-colour selection is designed to operate.

We note that our final CLASH sample features one object at $z_{\text{phot}} = 11.2$ (M0647-11-1). This object was first discovered by Coe et al. (2013) as JD1. In that study, Coe et al. identified two possible counter images of this object: JD2 and JD3. Based on our photometry, we could not confirm the high-redshift solution for JD2, and so it is not included here. Our SED fitting analysis of JD3 produces a primary high-redshift solution at $z = 10.3^{+0.5}_{-0.3}$ and this object is listed in Table 2 as M0647-10-1.

4 THE LUMINOSITY FUNCTION AT $z = 9$: BLANK-FIELD METHOD

4.1 Effective search area

By analysing the local depth maps, object selection and effective survey area can be usefully confined to only the cleanest and deepest regions of the *HST* imaging. As in McLeod et al. (2015), we refer to this as the ‘blank-field’ method for determining the $z = 9$ LF. For the HFF the depth cut was chosen to be 28.0 mag in H_{160} (5σ at 85 per cent of total assuming a point source), as in McLeod et al. (2015), again meaning that we focus on regions where $\sigma_{160} \simeq 30$ mag (or deeper) in a 0.5-arcsec diameter aperture. For the CLASH fields the cut-off was $H_{160} = 26.8$ (5σ at 85 per cent of total).

In addition to imaging depth, one also has to consider the reduction in effective area produced by factoring in the magnification maps. For the HFF fields analysed here, we have employed the CATS (Richard et al. 2014) and Zitrin LTM (Zitrin et al. 2013) lensing maps. For the CLASH fields, two lensing maps have been publicly released, the NFW and LTM-Gauss (LTMG) models by Zitrin et al. (2013), and so the analysis was done using those. In Fig. 4, we plot the effective delensed area of our combined CLASH imaging as a function of the survey depth for the lensing models adopted.

The lensing maps were also used to calculate the magnification of each candidate. For each map, the magnification was based on the average model magnification within a 0.5-arcsec diameter aperture around each object. For this blank-field method, the magnification factor was taken as the average of the different model values, with the extremes as the error bounds.

Using the aforementioned magnitude cuts, the delensed areas found were 20.4 arcmin² (NFW) and 14.5 arcmin² (LTMG) for CLASH, with 18.6 arcmin² for HFF. For the latter, the area is completely dominated by the parallel fields, which together contribute around 16.5 arcmin² of effective survey area. The area adopted for the HFF clusters was the average area from the two lensing maps used.

Completeness was calculated following the prescription described in McLure et al. (2013). Briefly, for each of the HFF and CLASH fields, simulations were performed in which 1000 synthetic high-redshift sources were injected into the relevant area of the imaging. These sources were then recovered and analysed in an identical fashion to the real high-redshift candidates. This process was repeated many times, each repeat using random spatial coordinates for the synthetic sources, and the final completeness as a function of magnitude was taken as the average over all simulations. The area contribution from each field for each candidate was

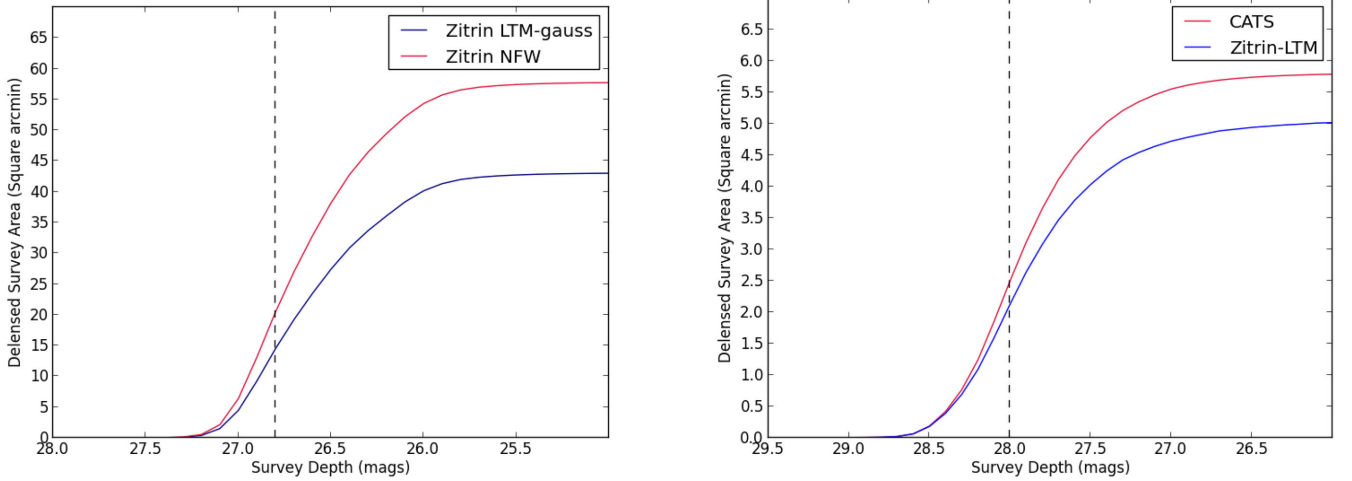


Figure 4. Left: the combined, effective, delensed survey area of the 20 CLASH clusters used in this study, as a function of the 5σ H_{160} depth. This illustrates the difference between the two different Zitrin et al. (2013) lensing models employed in this study. Right: the same, but for the four HFF cluster fields. The comparison here is between the two models by CATS and Zitrin et al. (LTM). For each plot, the adopted 5σ H_{160} depth limit is indicated by the dashed line; at $H_{160} = 28.0$ for the HFF imaging and $H_{160} = 26.8$ for the CLASH imaging. Although not shown here, the depth cut-off at $H_{160} = 28.0$ serves to retain $\simeq 85$ per cent of the total effective area available in the HFF parallel fields.

then scaled by its completeness fraction to calculate the number densities.

4.2 The $z = 9$ luminosity function

Using the $z \simeq 9$ blank-field sample, we are now in a position to better constrain the UV LF at this epoch. We find that none of the CLASH objects contributes to any LF determination in the blank-field approach. This is because they either lie in regions of the imaging that are shallower than the adopted cut-off limit or, when demagnified, they are intrinsically too faint to be detected if the field is assumed to be a blank one. Incompleteness prevents us from including the fainter, $M_{1500} > -18.7$, galaxies uncovered in the HFF pointings, but we can extend our study to fainter magnitudes by combining our new HFF results with the HUDF12 results at $z \simeq 9$ derived by McLure et al. (2013). This results in four luminosity bins at $z \simeq 9$, spanning the absolute magnitude range $-20.7 < M_{1500} < -17.25$. Finally, we did not find any galaxies brighter than $M_{1500} = -20.7$ in our search of CLASH and the HFF data sets, and therefore derive an upper limit at $\log_{10}\phi = -4.90$ at this magnitude (corresponding to a single object in the CLASH+HFF+HUDF volume searched).

These new results are presented in Fig. 5, which shows the $z \simeq 9$ UV LF as determined by restricting our analysis to the clean regions of the HFF and HUDF imaging, covering an area of $\simeq 22$ arcmin². The fainter two bins come from an area of $\simeq 4$ arcmin² provided by the HUDF alone. The upper limit at the bright end is derived from the unsuccessful search for $z \simeq 9$ candidates brighter than $M_{1500} = -20.7$ within a total area of $\simeq 45$ arcmin² from the CLASH, HFF and HUDF imaging which reached 5σ depths greater than 26.8 mag.

As also shown in Fig. 5, we have fitted a Schechter function (Schechter 1976) to the data. Because the data at $z \simeq 9$ still do not provide enough accuracy and/or dynamic range to allow a robust measurement of the faint-end slope, during the fitting this was held fixed at the $z \simeq 8$ value of $\alpha = -2.02$, as determined by McLure et al. (2013). We also cannot yet distinguish whether density or luminosity evolution better describes the evolution of the LF from $z \simeq 8$ to $z \simeq 9$, finding that the $z \simeq 9$ LF can be well described either

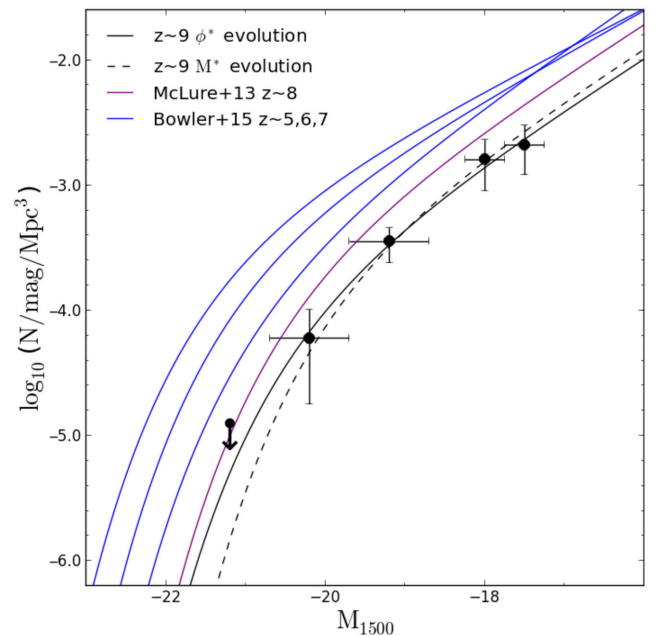


Figure 5. Our new determination of the UV LF at $z \simeq 9$ via the blank-field approach (i.e. constraining our search to the cleanest regions of the available HFF and CLASH imaging). The blue curves are the Schechter function fits to the $z = 5, 6$ and 7 LF from Bowler et al. (2015), while the purple curve is the $z = 8$ LF fit from McLure et al. (2013). The fainter bins corresponding to $M_{1500} = -17.5$ and -18.0 are from the HUDF study of McLure et al. (2013), while the brighter two bins at $M_{1500} = -19.2$ and -20.2 are the result of the present HFF study. An upper limit is included at $M_{1500} = -21.2$ resulting from our unsuccessful search for $z \simeq 9$ galaxies at these brighter magnitudes over the $\simeq 45$ arcmin² of combined HUDF+HFF+CLASH imaging of appropriate depth. Alternative Schechter function fits are shown at $z \simeq 9$, one assuming pure luminosity evolution from $z \simeq 8$ (dashed black line), and the other assuming pure number density evolution from $z \simeq 8$ (solid black line). The current data do not allow us to distinguish between these two simple alternative scenarios. In both of these fits the faint-end slope was set to the value derived by McLure et al. (2013) at $z \simeq 8$ (i.e. $\alpha = -2.02$).

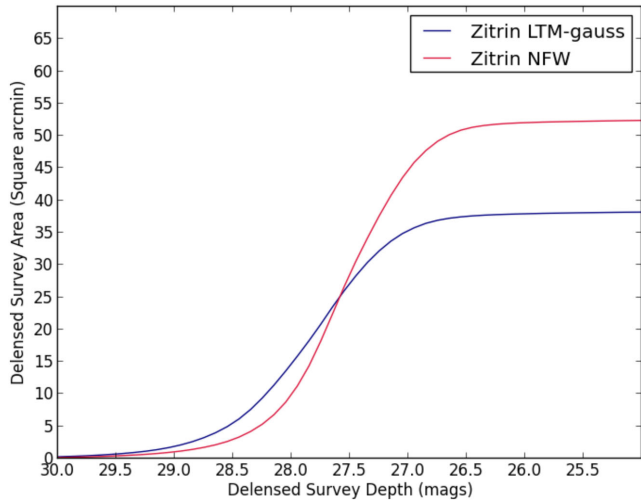


Figure 6. The effective area of the 20 CLASH cluster fields as a function of the delensed $J_{140} + H_{160}$ stack depth, for the two magnification models considered.

by a drop in density by a factor $\simeq 1.8$ to $\log_{10} \phi^* = -3.62^{+0.08}_{-0.10}$ (for a fixed $M^* = -20.1$), or by a dimming of the characteristic magnitude by $\simeq 0.45$ mag to $M^* = -19.65 \pm 0.15$ (for a fixed $\log_{10} \phi^* = -3.35$). These two alternative Schechter function fits at $z \simeq 9$ are both shown in Fig. 5, and are essentially indistinguishable from the $z \simeq 9$ LF fits derived and presented by McLeod et al. (2015).

As previously mentioned, these results are derived by adopting the average magnifications of the two alternative lensing models available for the new HFF fields. However, it can be seen from Fig. 4 that there is very little difference in the derived effective survey area between the different HFF lensing models for objects at our adopted blank-field magnitude limit.

5 THE LUMINOSITY FUNCTION AT $z = 9$: LENSED FIELD METHOD

5.1 Lensed areas

By adopting the blank-field method, none of our high-redshift candidates from the CLASH fields features in the $z = 9$ LF determination. To be as inclusive of our CLASH candidates as possible, we attempted to derive a LF using the full available area of the CLASH survey, including the more highly lensed regions. This comes with the risk of introducing biases in any derived number densities, due to uncertainties in the magnifications. As the majority of the CLASH candidates have come from a stacked image, the analysis was carried out on a $J_{140} + H_{160}$ stacked image for all fields. For each of the candidates, the effective area probed was calculated as the total delensed area over all fields, deep enough to detect the candidate at $\geq 5\sigma$ significance. The effective area calculation was performed independently for each of the lensing models. The delensed area–magnitude plots shown in Fig. 6 illustrate how this modifies the effective area calculations.

5.2 Lensed LF calculation

In Fig. 7 we present our alternative estimate of the $z = 9$ LF based on the lensed CLASH galaxies. We plot two alternative LFs, corresponding to the two alternative lensing models. Comparing with the

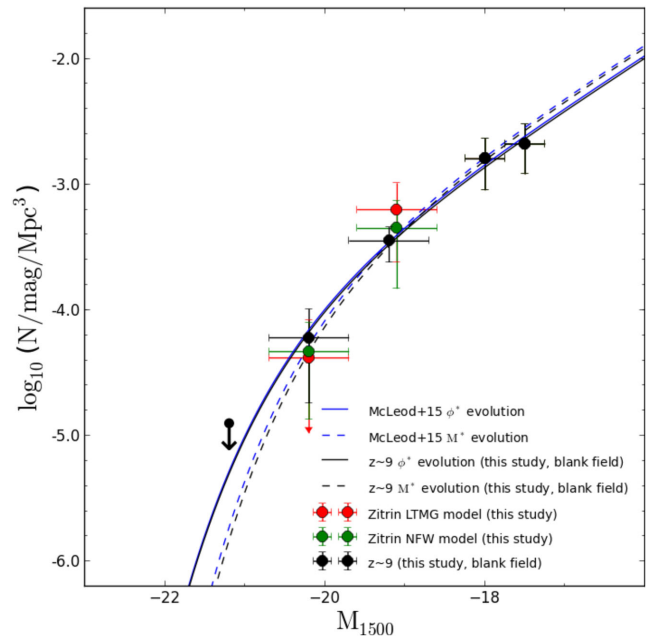


Figure 7. Our alternative determination of the UV LF at $z \simeq 9$ making fuller use of the search area in the CLASH fields. The black data points and curves show the blank-field LF determination from this study as already plotted in Fig. 5, while the coloured data points show the binned values resulting from the lensed field studies. For completeness, the blue curves show the McLeod et al. (2015) $z = 9$ fits, illustrating that our new results yield essentially identical Schechter function fits at $z = 9$. The lensed data points correspond to number densities assuming two different magnification models, the Zitrin et al. NFW model (green) and the Zitrin LTMG model (red). The $M_{1500} = -19.2$ lensed data points have been offset by $+0.1$ mag for clarity. This plot demonstrates that the results derived using either the blank-field or lensed-field methodology are very similar, but the blank-field approach yields more accurate and robust results.

blank-field LF determination derived earlier, it can be seen that the two methods are generally consistent. Although for the lensed case both models yield higher number densities in the fainter ($M_{1500} = -19.2$) bin, the results can all be comfortably reconciled through the large Poissonian uncertainties associated with such small number statistics. Because of the uncertainties between the models, we treat this alternative LF calculation simply as a consistency check. As the blank-field LF determination is less systematically biased, we adopt this as the best estimate of the $z = 9$ LF.

5.3 Extension to $z = 10$

As the vast majority of our $z \simeq 10$ candidates come from the CLASH fields (see Tables 1 and 2), the blank-field approach cannot yet be used to determine a meaningful estimate of galaxy number densities at $z \simeq 10$. Adopting the full-area lensed approach, depending on the assumed lensing model, we have either five candidates (NFW model) or three candidates (LTMG model) that can be placed in an absolute magnitude bin centred at $M_{1500} = -19.7$ at $z \simeq 10$. One of the candidates comes from the HFF (HFF4P-10-1), with the rest coming from the CLASH survey. The overall search area contribution from the HFF, and the number density contribution from the sole HFF candidate, was found to be very similar whatever magnification model was adopted, in part due to the dominance of the parallel fields. In the following we have adopted the CATS

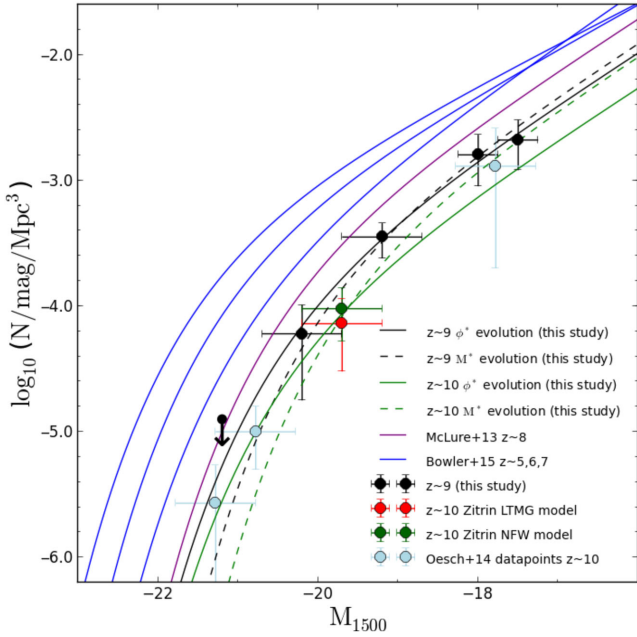


Figure 8. This plot shows the same information as shown in Fig. 5, but now includes our estimate of ϕ at $M_{1500} = -19.7$ at $z \simeq 10$. The Schechter function fit is again fitted in two ways while locking the faint-end slope at the $z \simeq 8$ value – one assuming pure luminosity evolution from $z \simeq 9$, and the other assuming pure number density evolution from $z \simeq 9$. The two alternative $z = 10$ data points result from adopting either the Zitrin et al. NFW lensing model or the Zitrin et al. LTMG lensing model. The inferred Schechter function was found to evolve very similarly between $z = 9$ and 10 as between $z = 8$ and 9, with either a further decline in characteristic number density by a factor of 2, or a dimming in M^* by a further $\simeq 0.25$ mag. The $z = 10$ results from Oesch et al. (2014) are also plotted. These points appear consistent with our new estimate of number density at $M_{1500} = -19.7$. Although the Schechter function was not fitted to these points the agreement with our pure number density evolution parametrization at the bright end is good, although the faintest Oesch et al. data point marginally favours luminosity evolution and/or further steepening of the faint-end slope.

magnification model for the HFF data, but the result is very similar if we substitute this for the Zitrin et al. LTM model.

We present our resulting alternative estimates of galaxy comoving number density at $z \simeq 10$ in a single luminosity bin in Fig. 8. This figure also shows our $z \simeq 9$ results, as well as other recent comoving number densities derived at $z \simeq 10$ by Oesch et al. (2014). We have fitted a Schechter function through the average of our $z \simeq 10$ data points, again fixing α at -2.02 and assuming either pure ϕ^* or pure M^* evolution (fixing the other parameter as appropriate). For density evolution, we find that ϕ^* evolves in a similar manner between $z = 9$ and 10 as between $z = 8$ and 9, with a further inferred decrease of a factor $\simeq 2$ to $\log_{10}\phi^* = -3.90^{+0.13}_{-0.20}$. For luminosity evolution, we find that the M^* dims by $\simeq 0.25$ mag from $z \simeq 9$ to $\simeq 10$, to $M^* = -19.41 \pm 0.17$. Although it is clearly difficult to draw detailed conclusions from a single data point, the LF at $z \simeq 10$ appears to reflect a smooth extrapolation of the evolution found between $z = 8$ and 9.

6 EVOLUTION OF LUMINOSITY DENSITY AT $z > 8$

Given our improved measurement of the galaxy UV LF at $z = 9$, and our new estimate of the likely evolution to $z \simeq 10$, we now revisit the evolution of UV luminosity density (ρ_{UV}) at these early epochs. As

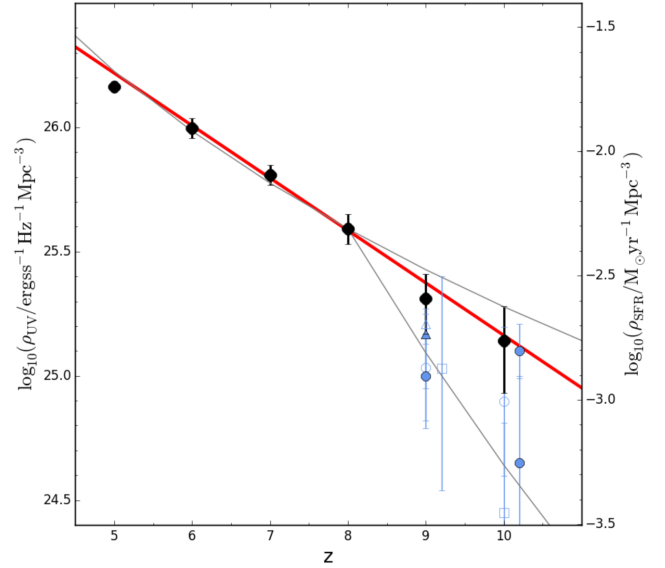


Figure 9. The evolution of the UV luminosity density, ρ_{UV} , and hence inferred star formation rate density, ρ_{SFR} , at $z > 5$, including our new measurements at $z = 9$ and 10. At $z = 9$ and 10, the results of several other recent studies are also plotted – open circles, filled circles, open triangles, filled triangles and open squares correspond to results from Ellis et al. (2013), Oesch et al. (2014), where the $z = 10$ points have been offset $+0.2$ in redshift for clarity, McLure et al. (2013), Ishigaki et al. (2015) and Bouwens et al. (2015a), respectively. Our measurements come from integrating the luminosity-weighted Schechter function LFs presented in Fig. 8 down to $M_{1500} = -17.7$, to facilitate straightforward comparison with the other results from the literature. The lower (Oesch et al. 2014) $z = 10$ data point corresponds to the ρ_{UV} computed directly from their candidates, while the upper data point is found by integrating their Schechter function assuming M^* evolution, as with this study. The secondary y-axis gives the star formation rate density, ρ_{SFR} , which is derived from ρ_{UV} assuming the conversion of Madau, Pozzetti & Dickinson (1998) with a Salpeter IMF. Given that our new estimate of ρ_{UV} at $z \simeq 9$ is so similar to that of McLeod et al. (2015), we have not replotted our earlier result. Overplotted in grey is the power-law function $\rho_{UV} \propto (1+z)^{-3.6}$ which is one possible simple extrapolation of ρ_{UV} beyond $z > 6$, and the steeper evolution following $\rho_{UV} \propto (1+z)^{-10.9}$, as both proposed by Oesch et al. (2014). As our data points do not conform to either of these extreme alternatives, we investigated what power-law index would give the best fit, or whether a linear fit to the data would fare better. As shown by the red line, we find that a linear relation of the form $\log_{10}(\rho_{UV}) = -0.211(\pm 0.028)z + 27.273(\pm 0.193)$ provides a good fit to our new estimates of ρ_{UV} . An alternative is a power law of the form $\rho_{UV} \propto (1+z)^{-5.8}$ which is also consistent with our new estimates (not shown).

discussed in the Introduction, this is currently the subject of some debate and controversy, given the conclusion reached by several recent studies (e.g. Oesch et al. 2014; Bouwens et al. 2015b), that there is a dramatic fall-off in ρ_{UV} at $z \geq 8$.

To facilitate comparison with these recent results, we perform the luminosity-weighted integration of the best-fitting Schechter functions shown in Fig. 8 (adopting the luminosity-evolved fits indicated by the dashed lines) down to a faint-end magnitude limit of $M_{1500} = -17.7$. When performing this calculation we do not dust correct the data, meaning that we are deliberately calculating the observed UV luminosity density. However, it should be noted that at $z \geq 7$, dust correcting using standard techniques (i.e. based on the average UV slopes; see Meurer et al. 1999) has a negligible impact on the derived values of ρ_{UV} . As can be seen in Fig. 9, we find $\log_{10}(\rho_{UV}/\text{erg s}^{-1} \text{Hz}^{-1} \text{Mpc}^{-3}) = 25.31^{+0.10}_{-0.14}$ at $z \simeq 9$, and

$\log_{10} \rho_{UV} = 25.14^{+0.14}_{-0.21}$ at $z \simeq 10$. We convert this into a comoving star formation rate density, ρ_{SFR} , by assuming the conversion of Madau et al. (1998) and a Salpeter IMF, which yields $\log_{10} \rho_{SFR} = -2.59^{+0.10}_{-0.14}$ at $z \simeq 9$ and $\log_{10} \rho_{SFR} = -2.76^{+0.14}_{-0.21}$ at $z \simeq 10$ (as also shown in Fig. 9, reading from the right-hand axis).

It is clear from Fig. 9 that our new determinations lie between the two extreme alternative extrapolations of the evolution of ρ_{SFR} beyond $z \simeq 8$ discussed by Oesch et al. (2014). Instead, our new results provide further support for the smooth decline of ρ_{UV} to high redshifts as deduced by McLeod et al. (2015), which can be reasonably described via a linear relation between $\log_{10} \rho_{UV}$ and z . With our new expanded data set, the best-fitting linear relation at $z \geq 6$ is given by $\log_{10}(\rho_{UV}) = -0.211(\pm 0.028)z + 27.273(\pm 0.193)$, and this is plotted as the red line in Fig. 9. Alternatively, if one wants to adopt a power-law relation in $(1+z)$, then we find that $\propto (1+z)^{-5.8}$ also provides a good description of the decline in ρ_{UV} beyond $z \simeq 8$.

Before moving on, it is worth briefly considering potential explanations for the variation in observational ρ_{SFR} estimates at $z = 9-10$. Undoubtedly, studies of the $z = 9-10$ galaxy population are still significantly affected by field-to-field variance. Many of the studies to date have either been based on a single WFC3/IR pointing (HUDF), or small numbers of WFC3/IR pointings from the HFF. The potential problems introduced by this can readily be seen from our own analysis of the HFF data set (see Table 1). Based on our analysis we identified four $z \simeq 9$ candidates in the first HFF cluster+parallel data set, 10 in the second and zero in the third. However, it is also the case that some of the apparent discrepancies are caused by differences in how ρ_{SFR} is calculated. A good example of this problem can be illustrated by comparing our estimate of ρ_{SFR} at $z \simeq 10$ with the results of Oesch et al. (2014). The headline result from Oesch et al. (2014) is that $\log_{10}(\rho_{SFR}) = -3.25 \pm 0.35$ at $z \simeq 10$ (lower data point in Fig. 9), which is in poor agreement with the value of $\log_{10}(\rho_{SFR}) = -2.76^{+0.14}_{-0.21}$ derived here. However, it is worth noting that the value of $\log_{10}(\rho_{SFR}) = -3.25 \pm 0.35$ was calculated by summing the contribution of the five $z \simeq 10$ candidates found by Oesch et al. (2014), rather than integrating their estimated $z \simeq 10$ LF to a consistent UV luminosity limit. Interestingly, Oesch et al. (2014) also calculate an alternative value of $\log_{10}(\rho_{SFR}) = -2.80 \pm 0.11$ (upper data point in Fig. 9), based on assuming luminosity evolution of the LF (as adopted here) and integrating to our adopted limit of $M_{1500} = -17.7$. This estimate of ρ_{SFR} is in excellent agreement with both our new determination at $z \simeq 10$, and our best-fitting linear $\rho_{SFR}-z$ relation.

Finally, it is interesting to compare our new observational estimate of the high-redshift evolution of ρ_{UV} with the predictions of recently published models of galaxy evolution.

Our data points are plotted against the predictions of seven such models in Fig. 10. It is important to acknowledge that some of these predictions are at least partly based on hydrodynamic simulations, while others are semi-analytic models, some of which have been effectively tuned to reproduce the UV LF at moderately high redshift (e.g. $z \simeq 6$). Thus, in a sense, this comparison is not completely fair, and cannot be simply regarded as specifically favouring one form of model over another. Nevertheless, some important general trends can be deduced. In particular, the Illustris (Genel et al. 2014) and Munich (Henriques et al. 2015) models, while clearly capable of reproducing many (often quite complex) aspects of galaxy evolution, both clearly underpredict ρ_{UV} at redshifts higher than $z \simeq 7$. We stress that this discrepancy is already clear by $z \simeq 8$ (where the measured value of ρ_{UV} is well established) and is simply confirmed and strengthened by our new results at $z \simeq 9$ and $\simeq 10$.

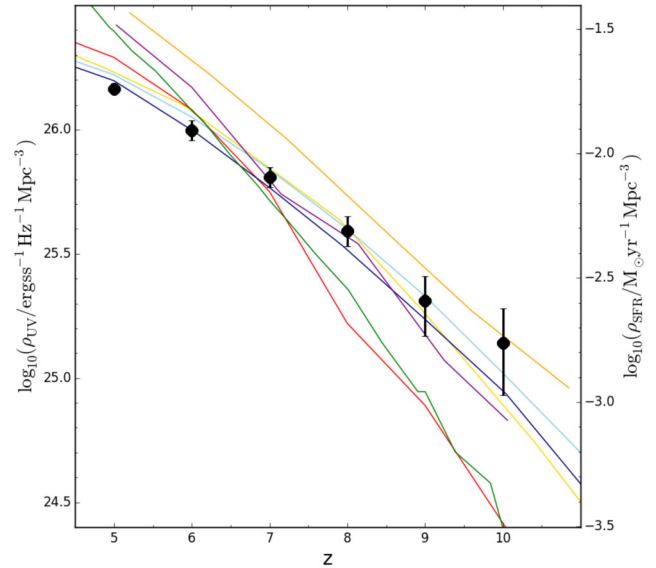


Figure 10. Our new measurement of the evolution of the UV luminosity density (ρ_{UV}) and inferred star-formation rate density (ρ_{SFR}) at $z > 5$, compared with the predictions of a range of models and simulations from the literature. The model predictions are as follows: the Illustris hydrosim (Genel et al. 2014, green curve), Khochfar et al., in preparation, hydro-sim (purple curve), Behroozi & Silk (2015) analytic model (orange curve) and the semi-analytic models from Munich (Henriques et al. 2015) (red curve), Cai et al. (2014) (light blue curve), Dayal, Mesinger & Pacucci (2015) (dark blue curve) and Mason et al. (2015) (yellow curve). Both the Illustris and Munich models under-predict the high-redshift luminosity density; this discrepancy is already clear by $z \simeq 8$ and is simply confirmed by our new results at $z \simeq 9$ and $z \simeq 10$. By contrast, most of the simple models which basically apply scaling relations to map the underlying halo mass function on to the UV LF deliver predictions in reasonably good agreement with our results.

The challenge, then, for such models is to be able to produce star formation activity which extends to higher redshifts than currently predicted. Indeed, the only model shown here that systematically overpredicts ρ_{UV} is that of Behroozi & Silk (2015). We note that the overprediction of raw observed ρ_{UV} at redshifts $z \simeq 5-6$ by the Illustris and Khochfar et al. simulations is not really a fundamental problem, as both of these models do not include the impact of dust obscuration.

Although the Khochfar et al. simulation produces more star formation rate density at higher redshift than either the Illustris or Munich models, the best predictions are produced by the fairly simple analytic models of Dayal et al. (2015), Cai et al. (2014) and Mason et al. (2015). This might be regarded as unsurprising given that, as mentioned above, these models are to some extent based on mappings between the dark matter halo mass function and the UV LF that have been ‘calibrated’ at high redshift. Nevertheless, the fact that such models do such a good job in reproducing the rate of decline in ρ_{UV} from $z \simeq 5$ to $\simeq 10$ is surely not a coincidence, and implies that galaxy evolution at these early times is indeed fairly simple, and driven primarily by the growth in the underlying dark matter.

As final evidence in support of this basic result, in Fig. 11 we compare our results with the generic analytic prediction of the high-redshift evolution of ρ_{SFR} deduced by Hernquist & Springel (2003). As a result of an effort to understand the physical processes driving the cosmic star formation rate, Hernquist & Springel (2003) predicted that at high redshift, beyond its peak, ρ_{SFR} should decline

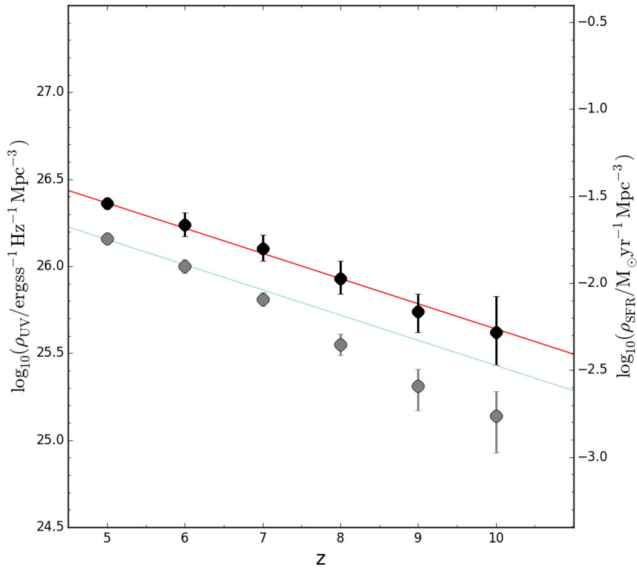


Figure 11. Our measurement of the evolution of the comoving UV luminosity density at $z > 5$ obtained by integrating the luminosity-weighted LF down to a limit of $M_{1500} = -17.7$ (grey points, as already plotted in Figs 9 and 10) and by integrating down to a fainter luminosity limit of $M_{1500} = -15$ (black points). The theoretical rate of decline of $\rho_{\text{SFR}} \propto \exp(-z/3)$ predicted by the analytic work of Hernquist & Springel (2003) is overplotted for both cases (scaled to match at $z \simeq 5$, to highlight the comparison between the observed and predicted rate of decline at higher redshift). While our results based on the shallower integration can, as already shown in Fig. 9, be described by a linear relation between $\log_{10} \rho_{\text{UV}}$ and z , the slope of this relation is clearly steeper than predicted by Hernquist & Springel (2003). However, by simply integrating down to $M_{1500} = -15$, to provide a more complete measurement of ρ_{UV} (especially at high redshift), it can be seen that the observed and predicted rate of decline of ρ_{UV} shift into excellent agreement.

smoothly in a manner very well approximated by the simple relation $\rho_{\text{SFR}} \propto \exp(-z/3)$. In other words, in the absence of significant dust obscuration, they predicted a linear descent of $\log_{10} \rho_{\text{UV}}$ with z , and predicted the *slope* of this relation based on the assumption that the evolution is driven simply by the growth of the underlying dark matter. In Fig. 11 we show our derived evolution of ρ_{UV} integrated down to $M_{1500} = -17.7$ (as previously plotted in Figs 9 and 10), but also show the results of integrating down by approximately another order-of-magnitude in luminosity, to $M_{1500} = -15$. Interestingly, while the results based on the shallower integration can, as already shown in Fig. 9, be described by a linear relation between $\log_{10} \rho_{\text{UV}}$ and z , the slope of this relation is clearly steeper than predicted by Hernquist & Springel (2003). However, by simply integrating down to $M_{1500} = -15$, to provide a more complete measurement of ρ_{UV} (especially at high redshift), it can be seen that the observed and predicted rate of decline of ρ_{UV} shift into excellent agreement.

7 CONCLUSIONS

In this study we have assembled the largest sample of $z \sim 9$ –11 galaxy candidates to date, identifying a total of 33 candidates in the redshift range $8.4 < z_{\text{phot}} < 11.2$ from the HFF and CLASH data sets. When combined with four candidates identified from our previous analysis of the HUDF, our final sample consists of 37 galaxy candidates at $z \geq 8.4$ selected from 29 independent WFC3/IR pointings (total area $\simeq 130 \text{ arcmin}^2$). Based on this sample we have produced an improved measurement of the UV-selected galaxy LF

at $z \simeq 9$ and placed initial constraints on the LF at $z \simeq 10$. In addition, we have revisited the issue of the decline in UV luminosity density at $z \geq 8$. Our main conclusions can be summarized as follows.

- (i) Employing an analysis restricted to the uniformly deep, and low magnification, regions of the HFF+HUDF data sets, we have derived an improved measurement of the UV-selected galaxy LF at $z \simeq 9$. Based on this ‘blank-field’ method, our new results strengthen the evidence that the LF continues to evolve smoothly between $z = 8$ and 9. Specifically, within this redshift interval, we find that the evolution of the LF can be equally well described by a 0.5 mag dimming in M^* (pure luminosity evolution) or a factor of $\simeq 2$ drop in ϕ^* (pure density evolution).
- (ii) As a consistency check, we have also used the full lensed area of our CLASH survey data set to derive an independent estimate of the $z \simeq 9$ LF. The determinations of the $z \simeq 9$ LF based on the blank field and lensed samples are found to be fully consistent.
- (iii) Using the combined CLASH+HFF+HUDF data sets we have derived initial constraints on the UV-selected galaxy LF at $z \simeq 10$. We find that the number density of $z \simeq 10$ galaxies at $M_{1500} \simeq -19.7$ is $\log_{10} \phi = -4.1^{+0.2}_{-0.3}$, a factor of $\simeq 2$ lower than at $z = 9$.
- (iv) Based on our new results we have revisited the issue of the decline in UV luminosity density at $z \geq 8$. We conclude that the data continue to support a smooth decline in ρ_{UV} over the interval $6 < z < 10$, in agreement with simple models of galaxy evolution driven by the growth in the underlying dark matter halo mass function.

ACKNOWLEDGEMENTS

We would like to thank the anonymous referee for comments and suggestions which improved the paper. DJM and RJM acknowledge the support of the European Research Council via the award of a Consolidator Grant (PI: McLure). JSD acknowledges the support of the European Research Council via the award of an Advanced Grant, and the contribution of the EC FP7 SPACE project ASTRODEEP (Ref. No.: 312725). This work is based in part on observations made with the NASA/ESA *Hubble Space Telescope*, which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS5-26555. This work is also based in part on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under NASA contract 1407.

This work utilizes gravitational lensing models produced by PIs: Bradač, Natarajan & Kneib (CATS), Merten & Zitrin, Sharon and Williams funded as part of the *HST* Frontier Fields program conducted by STScI. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555. The lens models were obtained from the Mikulski Archive for Space Telescopes (MAST). For CLASH we also used mass models constructed by Zitrin et al. (2013, 2015), obtained through the *Hubble Space Telescope* Archive, as a high-end science product.

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